NEW X-RAY IMAGING STRATEGIES: IMPLICATION FOR COCHLEAR IMPLANTATION

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INTRODUCTION

By continuous and simultaneous table translation, source rotation and data acquisition, spiral CT allows rapid volumetric imaging, and is especially valuable or pre- and post-operative evaluation of cochlear implant patients, despite limited resolution. Compared to radiography, spiral CT provides 3D images of the inner ear with nearly isotropic resolution, allows interactive visualization and quantitative analyses of the individual cochlear anatomy. Compared to other tomographic imaging modalities, spiral CT is the best choice when bony and metallic structures are involved.

Temporal bone imaging demands highest image resolution in 3D, especially so for cochlear implantation, because the anatomy of the inner ear is intricately 3D, and the dimensions of both the inner ear features and the intracochlear electrodes are typically in the sub-mm domain [1-6]. Pre-operatively, temporal bone imaging is important for assessing feasibility of cochlear implantation, selecting an ear for implantation, planning surgery, and improving insertion procedures. Post-operatively, imaging is needed for determining electrode positions relative to the cochlear anatomy, programming the speech processor, and assessing extent or rate of extrusion in cases with sudden or significant, progressive decrements in hearing and speech recognition. There is a critical and immediate need to geometrically model the individual cochlea *in vivo* with precise anatomic localization of implanted electrodes. This geometric model is a prerequisite for development of accurate electroanatomic models of the implanted cochlea, and may help explain part of the intersubject speech recognition variability that cannot be currently explained. Rational design of interventions, devices, and their programming are based on knowledge of geometric relations between an implantee's electrode array and intracochlear features.

We are committed to X-ray imaging for cochlear implantation. Over past several years, we have been developing several techniques that are critically important for geometric modeling of individual cochleae. These techniques include image deblurring, unwrapping, modeling and visualization, and will be described in the following sections.

IMAGE DEBLURRING

Spiral CT for imaging the cochlea and implant geometry can be improved by image deblurring, which is the established methodology to achieve super-resolution retrospectively. It was recently proved that the solution by the EM-like iterative deblurring fits data nonnegatively and optimally in a deterministic sense. We developed an EM-like spiral CT image deblurring methodology for volumetric or oblique sectional resolution enhancement [7]. Specifically, we found experimentally that the Gaussian blurring model approximates spiral CT quite well. Then, we developed a regularized EM-like algorithm for spiral CT image deblurring. A cochlear cross-section phantom was synthesized based on histologic and CT images, consisting of three types of structures: fluid, tissue and bone. A blurred noisy version of this phantom was deblurred using our method. After regularized deblurring, the system blurring was reduced by up to 30-40% according to the above criterion, without significant noise and ringing artifacts. Also, a CT resolution phantom, pre- and post-implantation patients were scanned, reconstructed into volumes of 0.1 mm isotropic voxels using a spiral CT scanner, and successfully deblurred using our iterative deblurring algorithm. Figure 1 shows a spiral CT slice and its deblurred version. Image resolution enhanced via deblurring is indicated by better defined bony features.

COCHLEAR UNWRAPPING

By computationally unwrapping an implanted electrode array in a spiral CT image into an elongated volume along the array axis, longitudinal and cross-

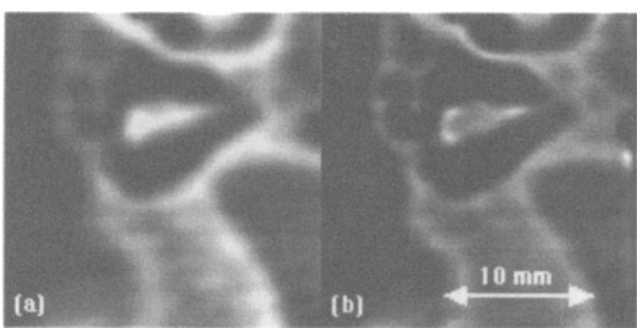

Figure 1. Digital deblurring of a spiral CT image. (a) A spiral CT image through the incus scanned using a cochlear implantation protocol, (b) post-processed using the EM-like iterative deblurring algorithm.

sectional positions of individual electrodes can be inferred based on a priori knowledge on the array. We designed an unwrapping algorithm to track and uncoil the implant array [8]. The unwrapping algorithm is illustrated in Figure 2. Briefly speaking, from a starting point along a reference local direction and with a specified step length, the next central axis point is estimated, adjusted to the mass center of the orthogonal cross-section passing through the estimated point, and scaled to have the specified step length. This procedure is repeated until an end point is sufficiently close. Once an implant array is automatically tracked, the cross-sections orthogonal to the array central axis can be digitally formed and stacked to straighten the curvilinear structure. The optimal tracking step length corresponds to the minimum average turning angle of the arc increment vector. Representative curvilinear structures were digitally synthesized. Demonstration electrode arrays, physical wire phantoms and 20 implanted patients were scanned and reconstructed into image volumes of 0.1 mm cubic voxels. Our unwrapping algorithm performed accurately in the numerical and *in vitro* experiments with an up to 2% error. The unwrapping estimates of the electrode array insertion depth for the 20 patients were consistent with those produced using Ketten's method based on inter-turn radii and axial height measured for each patient from spiral CT images [3]. Intraoperative estimates of insertion depth were about 1 mm longer on average because array compression and distortion were not detectable [3]. Further work is being performed to unwrap with respect to the central path of the cochlear canal, instead of that of the implant array.

3D MODELING AND VISUALIZATION

An average human cochlea was geometrically modeled based on histologic data. This model was originally applied to manual measurement from CT images obtained at 1 mm intervals. Canal lengths were calculated using Ketten and Wartzok's method via Archimedean spiral fitting. With spiral CT image deblurring, unwrapping, segmentation and modeling techniques as well as stereo-radiography, we are working on geometrical parameterization of the individual implanted cochlea *in vivo*. Accurate and efficient geometric descriptions will be formulated of

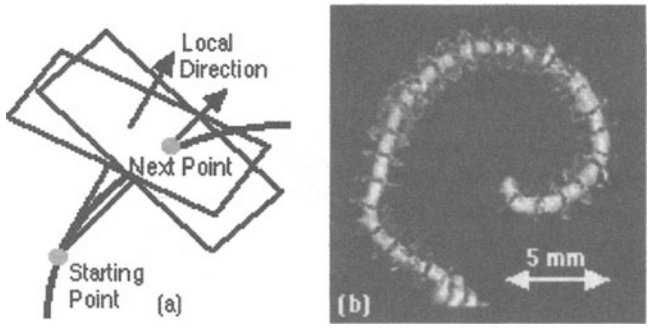

Figure 2. Digital unwrapping of a cochlear implant electrode array. (a) Diagram showing the unwrapping algorithm: from a starting point, the next point is estimated along the local direction, adjusted to the mass center of the cross-section orthogonal to the local direction, until an end point is reach; (b) the unwrapping method was applied to track a demonstration array, disks indicating cross-sections orthogonal to the array axis.

the cochlear anatomy and the implanted electrode array from digital radiographs and reconstruction of pre- and post-operative spiral CT for patients. Model-based features will be extracted. This model may be merged with a counterpart built from MRI, visualized using rendering and "fly-through" techniques, and analyzed for various features.

DISCUSSION

We acknowledge that factors other than implanted electrode positions and other geometric features affect variability of performance in terms of both speech recognition as well as threshold/dynamic range. These factors include (1) the number, position, and function of surviving first order auditory neurons, (2) the status and function of the central auditory pathways, (3) the patient's prior linguistic experience, and (4) the cognitive function of that patient. However, the knowledge of implanted electrode positions is important to describe the electrical fields they produce in each individual patient, hence help program the speech processor and improve the electrode array design for better delivery of electrical stimuli.

The significance of the project has broader scope than its contribution to cochlear implantation. For example, the proposed improvements, modeling and visualization of spiral CT images of the middle and inner ear would be a major technological advance in the clinical care of patients with ear disease. Also, the modeling and visualization software would be particularly valuable for training otolaryngology residents.

Eventually, our techniques will allow automatic generation of the individualized geometric models of the cochlea from pre- and post-operative spiral CT volumes, combined with the *in vivo* model of the implanted array derived using stereophotogrammetry. Also, our techniques may be integrated into a Web-based resource, and made readily available for applications in patient studies and basic research.

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